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(54) Fuel system for a gas turbine engine

(57) A fuel system for a gas turbine engine including an engine control unit 1 arranged to receive at least one input signal 3 responsive to at least one required engine operating condition and to give an output fuel demand signal 5 corresponding to the fuel flow required by the engine 4 when operating in accordance with the or each operating condition. The fuel system also includes an electrically-driven fuel pump 7 and a fuel pump control unit 6 connected to receive the fuel demand signal 5 and to compare that signal with an actual fuel pump speed signal 9 received from the fuel pump 7 and to alter the fuel pump speed until the fuel flow delivered to the engine 4 by the fuel pump 7 is equal to the fuel flow demand corresponding to the fuel demand signal 5.

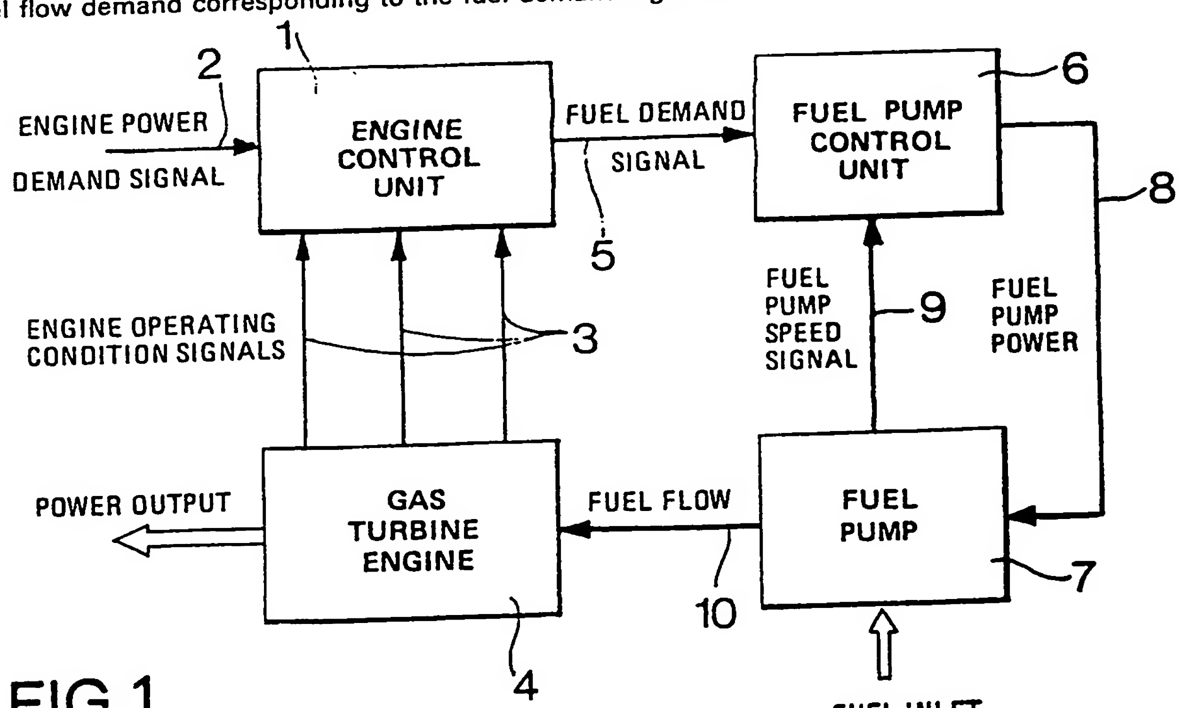

FIG.1

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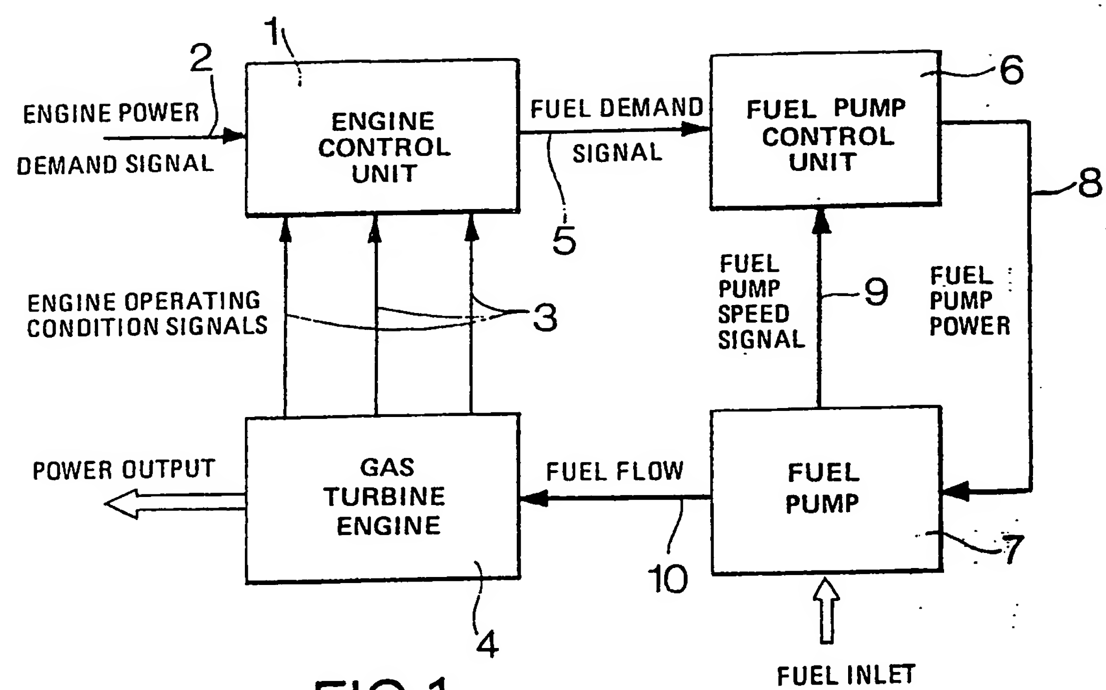

FIG.1

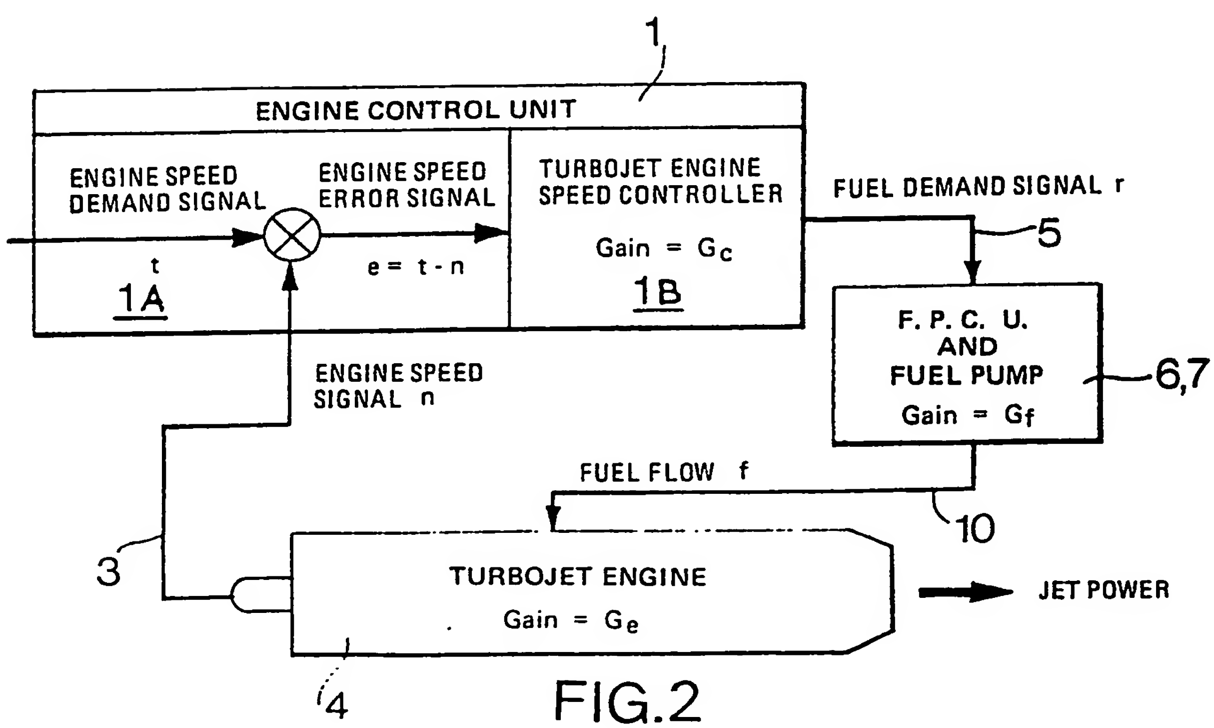

FIG.2

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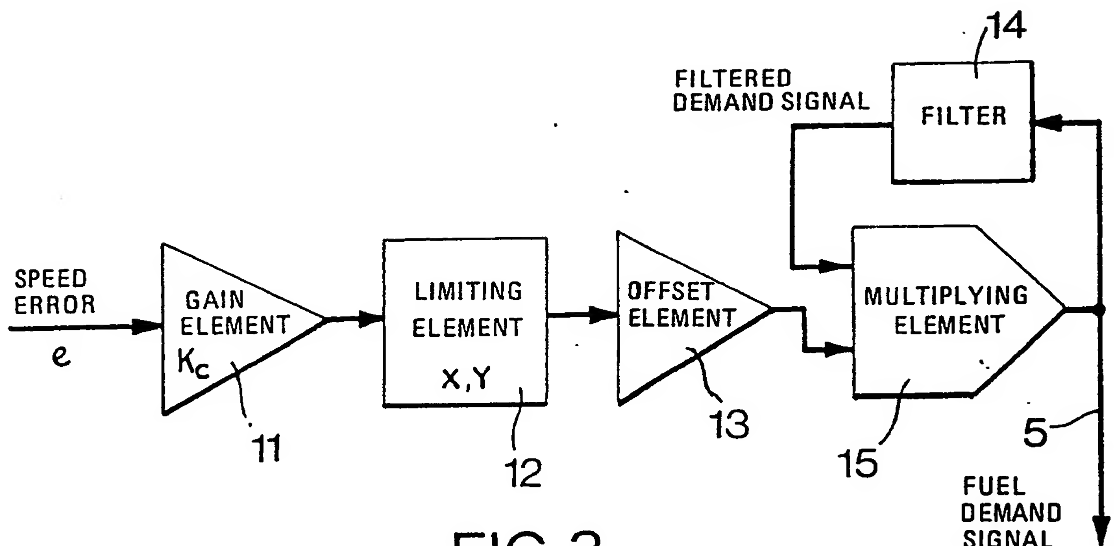
14
FILTERED
DEMAND SIGNAL
FILTER
SPEED
ERROR
e
GAIN
ELEMENT
K_c
LIMITING
ELEMENT
X,Y
OFFSET
ELEMENT
MULTIPLYING
ELEMENT
11
12
13
15
5
FUEL
DEMAND
SIGNAL

FIG.3

SPECIFICATION

Fuel system for a gas turbine engine

The invention relates to a fuel system for a gas turbine engine including a fuel pump by which the rate at which fuel is delivered to the engine determines the power produced.

The fuel system according to the invention relates particularly to a single shaft turbojet engine; but may be used to control the power output from a single or multiple shaft gas turbine engine, whether it is employed to produce a propulsive jet, shaft power, a stream of hot gas, or any combination of these outputs.

According to the invention, a fuel system for a gas turbine engine comprises an engine control unit arranged to receive at least one input signal responsive to at least one required engine operating condition and to give an output signal corresponding to the fuel flow required by the engine when operating in accordance with the or each said operating condition; a fuel pump and a fuel pump control unit connected to receive said output signal from the engine control unit and to compare said output signal with an actual fuel pump speed signal received from the fuel pump and to alter the fuel pump speed until the fuel flow delivered to the engine by the fuel pump is substantially equal to the fuel flow demand corresponding to said output signal from the engine control unit.

The fuel pump is conveniently driven by an electric motor and in that case, the fuel pump control unit includes electrical circuitry and is arranged to control the fuel pump electrically. The fuel pump employed is preferably of the kind having a constant flow characteristic, that is, it will pump quantities of fuel in proportion to the operating speed of the pump independently of the pressure of fuel delivered thereby. With a fuel pump of this kind, the speed of the electric motor may be so controlled by the fuel pump control unit that the latter will so adjust the electrical power supplied to the motor that the pump speed will vary in direct proportion to the desired fuel flow scheduled by the engine control unit.

The engine control unit may also include electrical circuitry and provide an electrical output signal corresponding to the desired pump speed in response to at least one electrical input signal derived from the engine and at least one electrical input signal corresponding to a desired engine operating condition. The input signals derived from the engine may relate to any one or more critical engine operating conditions, for example, shaft speed; pressure and temperature of working fluid at appropriate locations in the engine.

An important characteristic of the fuel system in accordance with the invention and as set out in the three immediately preceding paragraphs is that no mechanically-operable item such as a fuel valve is required to control fuel flow, because the fuel flow is controlled by the fuel pump control unit for all engine conditions. A shut-off valve may be provided for safety reasons between the fuel pump and the engine, such a valve would only operate to admit fuel to the engine or to completely block the fuel flow, that is, the shut-off safety valve would operate only as an on/off valve and would not operate as a rate of flow control valve. With the fuel system provided by the invention, no device other than a shut-off safety valve and the fuel pump itself together with the remainder of the fuel system is required to influence the flow of fuel to the engine. The number of moving parts is therefore reduced to a minimum. Additionally, the fuel system minimises the power required to pump fuel in that no energy is lost through a drop in pressure through a fuel control valve. The absence of a calibrated fuel control valve as is required in conventional fuel systems may permit lower standards of fuel filtering to be tolerated. Furthermore, the fuel system does not necessarily require specialised mechanical parts since the fuel pump, fuel pump motor and a shut-off valve are standard items available at comparatively low cost, the only specialised items being the engine control unit and the fuel pump control unit and any associated signal tapping devices.

The fuel system according to the invention is, as stated hereinbefore, applicable, in principle, to any type of gas turbine engine. The engine control unit is an important part of the fuel system as it must ensure that the delivered fuel flow is suited to the requirements of a particular engine as it operates in a particular application.

The invention therefore also provides an engine control unit for use in a fuel system as hereinbefore set out, the engine control unit comprising means to receive at least one input signal responsive to at least one required engine operating condition and means to give an output signal corresponding to the fuel flow required by the engine when operating in accordance with the or each said operating condition.

A particular engine control unit for use in a fuel system for a single shaft turbojet engine operating between idle and maximum speed and having means responsive to two input control signals, namely an engine speed demand signal corresponding to throttle setting and a signal responsive to actual engine speed also has means to determine the difference between these two input signals as an engine speed error signal and means to produce from the error signal an output fuel demand signal corresponding to the fuel required by the engine.

The engine control unit as set out in the immediately preceding paragraph is for practically the simplest conceivable engine and application and thus the engine control unit is correspondingly basic and may form the basis for a single shaft turbojet engine which requires fuel flow to be adjusted in response to more than one signal corresponding to more than one actual engine operating condition or it may form the basis for a gas turbine engine of any other type in any other application.

By way of example, a gas turbine fuel system and the aforesaid basic engine control unit therefore are now described with reference to the accompanying drawings, in which:–

Figure 1 is a diagram illustrating the fuel system;

Figure 2 is a diagram illustrating the fuel system, including elements of the engine control unit, for a single shaft turbojet engine having an engine speed demand signal corresponding to a throttle setting and an actual engine speed signal, and

Figure 3 is a diagram illustrating components of means in the engine control unit of Fig. 2 for producing the output fuel demand signal.

Referring to Fig. 1, the fuel system in accordance with this invention comprises the Engine Control Unit (E.C.U.) shown by block 1. This receives an engine power demand signal 2 determined by the throttle setting and also one or more input signals 3 which are feedback signals received from the engine 4 and responsive to one or more engine operating conditions, such as, for example, shaft speed or pressure or temperature of working fluid at appropriate locations in the engine. E.C.U., 1, as will hereinafter be explained, produces a Fuel Demand Signal 5 which is applied as an input signal to the Fuel Pump Control Unit (F.P.C.U.) shown by block 6. In this example the fuel pump 7 is driven by an electric motor and this is controlled by electrical circuitry in F.P.C.U. 6. The electrical driving connection between F.P.C.U. 6, and the fuel pump 7 is indicated at 8. As aforesaid the fuel pump 7 is preferably of the kind having a constant flow characteristic, that is, it will pump quantities of fuel in proportion to the operating speed of the pump independently of the pressure of fuel delivered thereby. The speed of the electric motor may be so controlled by F.P.C.U. 6, that the latter will so adjust the electrical power supplied to the motor that the pump speed will vary in direct porportion to the desired fuel flow scheduled by E.C.U. 1. The fuel pump 7 gives a speed feedback signal 9 to F.P.C.U. 6. The fuel pump 7 has a fuel inlet from a fuel tank or boost pump and delivers fuel at 10 to the engine 4.

In this example, the engine being controlled is a single shaft turbojet engine having only two input control signals, these being an engine speed demand signal corresponding to a throttle setting and a signal corresponding to actual engine speed. The Engine Control Unit (E.C.U.) 1 having these two input control signals is described with reference to Fig. 2, in which the engine speed demand signal is indicated as t and the engine speed signal is indicated as n. The difference between these two input signals is determined in part 1A of E.C.U. 1 as a speed error e. A single shaft turbojet engine controlled by E.C.U. 1 having only the two input signals t and n is practically the simplest conceivable application and so the E.C.U. is correspondingly basic and therefore forms the basis of a control unit either for an aircraft turbojet engine which requires fuel flow to be adjusted in response to more than one signal 3 corresponding to an engine operating condition or for a gas turbine engine of any other type in any other application. The basic functions that the E.C.U. is required to perform are now described.

The E.C.U. must provide a fuel flow control which:–

(1) controls engine speed according to throttle setting at all flight conditions;

(2) provides smooth accelerations and decelerations of engine speed as explained hereinafter;

(3) compensates for changes in air density due to changes in flight condition.

When the throttle setting is suddenly changed, the rate at which the fuel flow changes in response to change in power demand must be limited. When increased power is selected, the E.C.U. must prevent too large an increase in fuel occurring before the engine compressor has had time to increase its speed as otherwise, there could be overheating or reversal of air flow, i.e., surge. When a lower power is selected, the E.C.U. must prevent fuel flow from reducing so much that the flame is extinguished. Until the engine compressor has had time to reduce its speed, a high airflow is maintained through the engine and this might extinguish a lean flame, i.e., weak extinction.

The important factors to consider are engine speed n and fuel flow f. A consequence of change in air density in the engine is variation of engine gain G_e. This is defined as follows:–

$$\text{Engine gain, } G_e, = \frac{\text{change in engine speed}}{\text{change in fuel flow}} = \frac{\Delta n}{\Delta f}$$

It is important to match the fuel system to the engine so that changes in engine gain are compensated. If this is not done the fuel system will under respond to the speed error e when

the engine gain is low causing sluggish response to changes in power demand and will over respond to the speed error e when the engine gain is high. The latter condition is more serious since over-reaction of the fuel system to speed error e will cause the fuel system to be unstable and the engine will never settle to a steady controlled state. An important condition which must be correct is the loop gain, G_L. This is the product of the individual gains of all elements in the control loop as illustrated in Fig. 2.

Loop gain $G_L = G_c \cdot G_f \cdot G_e$, where:–

$$G_c = \text{engine control unit gain} = \frac{\text{change in fuel demand}}{\text{change in speed error}} = \frac{\Delta r}{\Delta e}$$

$$G_f = \text{fuel pump gain} = \frac{\text{change in fuel flow}}{\text{change in fuel demand}} = \frac{\Delta f}{\Delta r}$$

When the throttle setting t is unchanged, the change in speed error corresponds to the change in engine speed and so

$$\Delta e = \Delta t - \Delta n = -\Delta n \text{ because } \Delta t = 0$$

The operation of the E.C.U. described relies upon the fact that under all conditions the engine gain is inversely proportional to fuel flow. By making the gain of the E.C.U., G_c, proportional to pump speed, the loop gain, G_L, of the whole system is held constant.

For turbojet engines:–

$$G_c = \frac{K_e}{f}, \text{ where } K_e \text{ is a constant.}$$

For a fuel pump, where fuel flow is proportional to pump speed, and pump speed is proportional to the fuel demand signal:–

$$G_f = \frac{f}{r}$$

but by design, since pump speed is directly proportional to the fuel demand signal, the engine control gain is so arranged that

$$G_c = K_c \cdot r, \text{ where } K_c \text{ is a constant}$$

Therefore

$$G_L = K_e \cdot K_c$$

Thus loop gain, G_L, is constant and so its value is independent of the actual pump gain, G_f. This is useful, since, in practice, the pump gain can be made sensitive to small dimensional changes in the fuel pump and the engine fuel spray nozzles.

The part of the E.C.U. 1 which controls the engine speed in response to the engine speed error signal e is indicated in Fig. 2 as 1B and is shown in more detail in Fig. 3. The components of part 1B are as follows:–

(11) A simple gain element which multiplies the speed error e by the constant K_c;

(12) A limiting device which limits the output of gain element 11 between predetermined maximum and minimum values X and Y respectively;

(13) An offset element which adds one to the output of element 12

(14) a simple filter whose output reflects its input but lags in time, and

(15) a multiplying element which multiplies two inputs and has a continuous output equal to the product of the two inputs.

The two inputs are derived from the offset element 13 and the filter element 14 and the filter element 14 derives its input signal from the output of the multiplying element.

The output of the multiplying element is used as the fuel demand signal r which is applied at 5 to the F.P.C.U. 6.

The characteristic of the filter element is that of a simple exponential lag having a time constant of T seconds. This means that the value of the filter element is continuously trying to

catch up with the value of the input signal and succeeds in reducing the difference by approximately sixty per cent in every T seconds.

The functioning of the components of part 1B of the E.C.U. 1, is now described. When the engine speed error signal e is zero, the output of the offset element 13 is exactly one. Where the same engine speed and fuel flow have been maintained for a time significantly longer than T seconds, the output of the filter element 14 will have caught up with the input to the filter element 14 and will continuously feed a signal corresponding to the current average fuel demand signal into the multiplier element 15. The multiplier element 15 will multiply the output from the filter element by one and so the same fuel demand signal will be maintained indefinitely, provided that no speed error is detected in part 1A of E.C.U. 1.

Small fluctuations in engine speed are corrected in the following manner. A speed error will be detected in part 1A and be applied as input signal e to part 1B of E.C.U. If the engine speed is below the desired speed, the error e will have a positive value in order to increase the fuel flow and so reduce the speed error. The output of the offset element 13 will therefore be a corresponding amount greater than one. This number will be multiplied by the signal from the filter element 14 and so the value of the fuel flow demand signal at the output of the multiplier element 15 will be raised. Provided the duration of this speed-correcting sequence of events is small compared with the time constant T of the filter element, the output from the filter element will not be changed significantly and so the fuel flow demand will vary in direct proportion to the output signal from the offset element 13. The magnitude of the variations in the fuel demand signal will be proportional to the output from the filter element 14 and will correspond to an average fuel flow demand signal level. The part 1B of the E.C.U. 1 as shown in Fig. 3 therefore realises proportional control with variable gain which is proportional to average fuel flow.

If the engine speed error signal e is too large, the proportional changes in fuel flow from the average level will put the reliable operation of the engine at risk, for example by causing surge or flame extinction, as described hereinbefore. The limiting element 12 shown in Fig. 3 acts to prevent the fuel flow demand signal from changing by more than a certain fraction in such an instance.

This fraction corresponds to the value X for a sudden increase in fuel flow above the average level of fuel flow demand and to the value Y for a sudden decrease in fuel flow below the average level of fuel flow demand, the average level of fuel flow demand corresponding to the output signal from the filter element 14.

The functioning of the part 1B of E.C.U. 1, when the speed error e is large and enduring, for example, as it would be when the throttle setting is increased to raise the engine speed and power, is now described. The fuel flow demand signal will rise instantly above its previous steady average value, defined by the output of the filter element 14, by the fraction X defined by the limiting element 12. Thereafter, while the speed error continues to exceed the limiting fraction X, the fuel fow demand will continue to rise by virtue of a corresponding rise in the level of the output signal of the filter element 14 acting through the multiplier element 15. The rate of the said rise will be governed by the values of X and T and will be such as to provide a steady acceleration of engine speed and a smooth increase in engine power. The mathematical term for the way in which the fuel demand signal increases with time is exponential. This means that the rate of increase in the signal is proportional to the value of the signal at any instant. This characteristic is an acceptable approximation to the relationship between engine fuel flow and engine speed for a turbojet engine operating at any particular altitude and flight speed and thereby secures a steady acceleration. The value of X must correspond to the value of T for a particular application so that the instantaneous rise in fuel flow at the beginning of the engine acceleration will set the engine accelerating at a rate which is the same as the rate corresponding to the exponential increase in fuel flow which follows. When the engine speed has risen until the speed error has reduced sufficiently for the limit X no longer to be reached by the output of the limiting element 12, the fuel flow demand signal will once again have been brought under direct proportional control by the speed error with a gain corresponding to the new value of the fuel flow demand signal.

The E.C.U. 1 will function in a similar manner when the engine speed is reduced by throttling back. In that case, the exponential reduction of fuel flow will be governed by the value of limit Y in the limiting element 12.

From the foregoing description of operation, it will be apparent that long term values of fuel flow, that is during times greater than T second, are determined predominantly by the output of the filter element 14 and short term variations in fuel flow are governed by the output of the offset element 13. While the output of the offset element 13 is limited by the limiting element 12 so as to be independent of fluctuations in engine speed, the engine control system is said to operate in "open loop" manner. Operation in "open loop" during engine acceleration and deceleration has a favourable effect on the overall behaviour of the engine when operating with the fuel system provided by this invention and as described hereinbefore. Temporary open loop

operation allows the engine to respond quickly to changes in power demand without a need to alter the chosen value of loop gain, G_L, which prevails when the fuel system is maintaining the engine speed at a constant value.

In a typical turbojet application, the engine control unit parameters may have the following values:–

Loop Gain, $G_L = K_e \cdot K_c = 8$

Limiting element fuel flow excursion limits
$X = 10\%$
$Y = 10\%$

Filter element time constant

$T = 1.0$ seconds.

In this application, quoted by way of example, the fuel flow will increase instantly by 10% following an increase in power demand level and will thereafter increase at a rate of 10% per second until the engine attains the demanded shaft speed.

The functional element of E.C.U. for a turbojet engine are depicted in Fig. 3 by way of example to assist in the foregoing explanation of the way in which they control the engine. Any alternative arrangement of functional elements which secures similar relationships between speed control and fuel demand signals to control a gas turbine engine using a variable speed fuel pump may be provided and falls within the scope of this invention.

CLAIMS

1. A fuel system for a gas turbine engine comprising an engine control unit arranged to receive at least one input signal responsive to at least one required engine operating condition and to give an output signal corresponding to the fuel flow required by the engine when operating in accordance with the or each said operating condition; a fuel pump and a fuel pump control unit connected to receive said output signal from the engine control unit and to compare said output signal with an actual fuel pump speed signal received from the fuel pump and to alter the fuel pump speed until the fuel flow delivered to the engine by the fuel pump is substantially equal to the fuel flow demand corresponding to said output signal from the engine control unit.

2. A fuel system as claimed in Claim 1 in which the fuel pump is arranged to be driven by an electric motor and the fuel pump control unit includes electrical circuitry and is arranged to control the fuel pump electrically.

3. A fuel system as claimed in Claim 2 in which the fuel pump is of the kind having a constant flow characteristic and the speed of the electric motor is so controlled by the fuel pump control unit that the latter will adjust the electrical power supplied to the motor that the pump speed will vary in direct proportion to the desired fuel flow scheduled by the engine control unit.

4. A fuel system as claimed in any preceding claim in which the engine control unit includes electrical circuitry and provides an electrical output signal corresponding to the desired pump speed in response to at least one electrical input signal derived from the engine and at least one electrical input signal corresponding to a desired engine operating condition.

5. An engine control unit for use in a fuel system as claimed in any preceding claim in which the engine control unit comprises means to receive at least one input signal responsive to at least one required engine operating condition and means to give an output signal corresponding to the fuel flow required by the engine when operating in accordance with the or each said operating condition.

6. An engine control unit as claimed in Claim 5 for a single shaft turbojet engine operating between idle and maximum speed and having means responsive to two input control signals, namely an engine speed demand signal corresponding to throttle setting and a signal responsive to actual engine speed, the engine control unit also having means to determine the difference between these two input signals as an engine speed error signal and means to produce from the error signal an output fuel demand signal corresponding to the fuel required by the engine.

7. A fuel system for a gas turbine engine substantially as described herein with reference to the accompanying drawings.

8. An engine control unit for use in a fuel system for a gas turbine engine, the engine control unit being substantially as described herein with reference to the accompanying drawings.

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